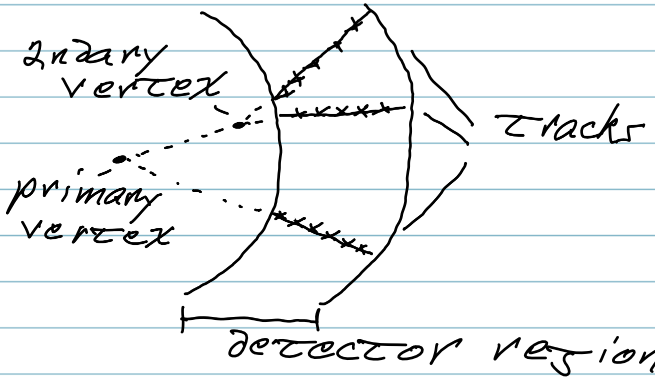
Tracking Detectors

- Critical to measure the trajectory of a particle
  - establish directionality
  - decay of unstable particles
    - find originating vertex

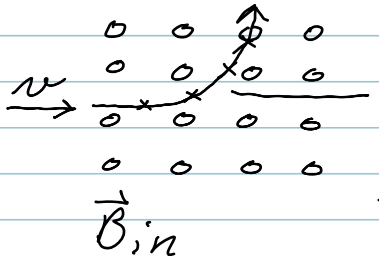
Example:
Drift chamber
- extrapolate tracks to interaction point



- Need a non-destructive position measurement
  - ionization
  - low # of X_0
- Vertex determination
  - requires very precise hit localization

Momentum Measurement

If a magnetic field:



observed track bends

- indicates charged particle trajectory curvature

→ gives momentum

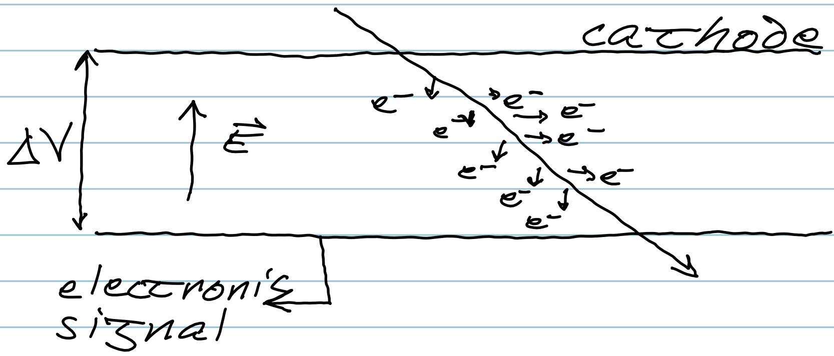
$$\vec{F} = q\vec{v} \times \vec{B}$$

- as v increases
  → bend decreases for a fixed B-field

3 categories of common trackers

- gaseous ionization detectors
- semiconductors
- scintillating fiber tracker

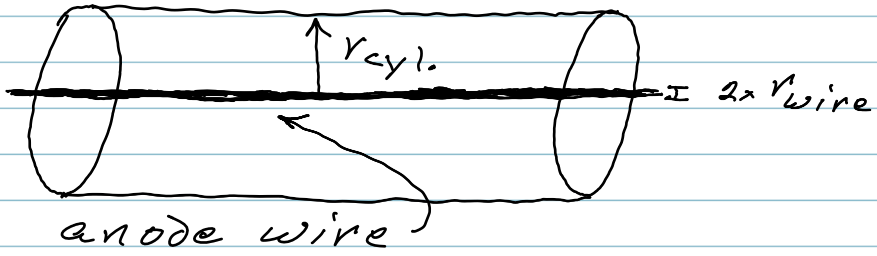
Proportional Detectors



When $\vec{E}$ is large enough

- primary e^- ionization
  - gets enough KE to cause more ionization
- if $\vec{E}$ lower than
  - avalanche threshold
  - $N_e \propto$ # of primary ion pairs (ie. dE/dx)

Cylindrical geometry



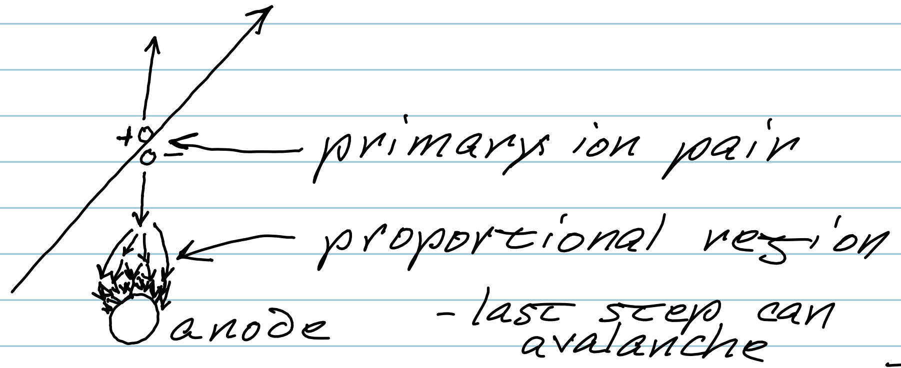
$$|E| = \frac{V_0}{r \ln(r_c/r_w)} \propto \frac{1}{r}$$

E-field highest near anode

- most secondary ionization there

Ionization Parameters in Gases

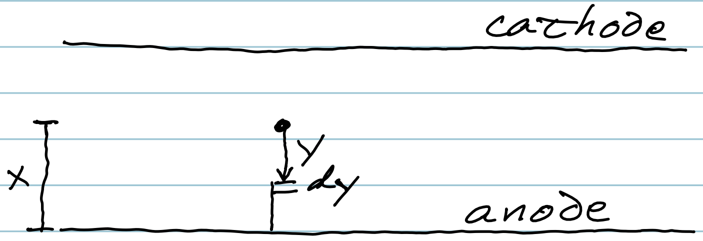
- secondary ionization
  - cross section maximized $E \sim 100$ eV (in Noble gases)
- primary ionization
  - some δ rays produce further ionization
  - γ's from atomic De-excitation
    - can result in ionization
  - # ions/unit length
    - varies with substance
- average energy lost per ion pair ~ 30 eV irrespective of gas



- last step can avalanche
  - many more e^-
  - last 20 μm or so

Simple Example

Ionization happens at location between electrodes



- more e^- as approach anode

$$dN = \alpha N\,dy$$

N = total # of free e^-s to anode

coefficient a function of
- E-field
- gas pressure

- the change in # e^-s yields:

$$\boxed{N(x) = N_0 e^{\alpha x}}$$

N_0 = # primary e^-s

Gas Amplification Factor

In practice

- speak of "total electron multiplication"

  - or

  "gas amplification factor"

$$M(x) = e^{\alpha x}$$

$$= \exp\left[\int_{r_k}^{r_w} \alpha(y)\, dy\right]$$

r_k - radius where $\mathcal{E}$ high enough to cause more ionization

In proportional counters

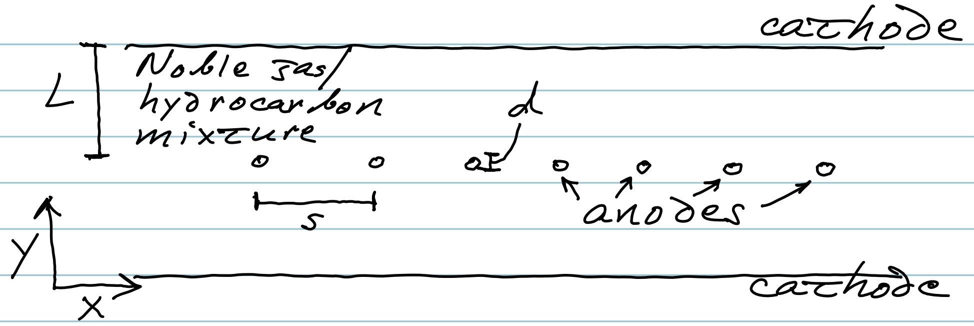
$$\boxed{M \rightarrow \text{constant} * e^{V_0/V_{ref}}}$$

= constant for a given experimental configuration

Multiwire Proportional Chamber

Configuration where anodes are thin wires

- sandwich a plane between cathode planes



L = anode-cathode spacing
~3-5x anode wire spacing
s = anode wire spacing (~2mm)
d = wire diameter (10-30μm)

Ability to collect charge on multiple wires

- improved spatial resolution

$$\underline{\sigma(x) \sim \frac{s}{\sqrt{12}}} = 580\mu m \; (s = 2mm)$$

113

Electrostatics

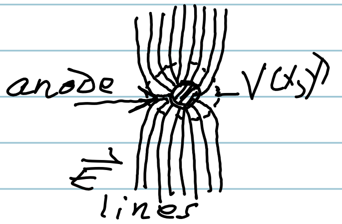
As wire diameter, $d \to 0$

$$\boxed{V(x,y) = \frac{C V_0}{4\pi\epsilon_0}\left\{\frac{2\pi L}{s} - \ln\left(4\sin^2\frac{\pi x}{s} + 4\sinh^2\frac{\pi y}{s}\right)\right\}}$$

$= V_0$ at anodes
$= 0$ at cathodes

In region of avalanche

- near anode
- nearly circular equipotential



$\therefore$ behave like proportional counter

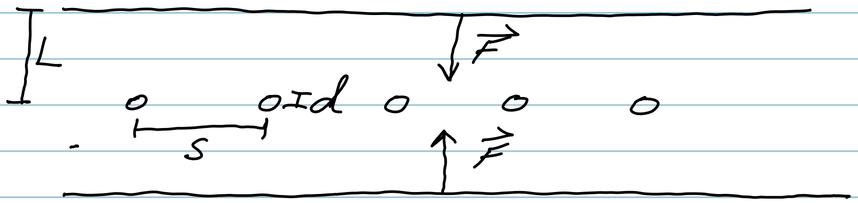
Capacitance associated

$$\boxed{C = \frac{2\pi\epsilon_0}{\frac{\pi L}{s} - \ln\left(\frac{\pi d}{s}\right)}}$$

If $s = 2\,\text{mm}$, $L = 8\,\text{mm}$, $d = 30\,\mu\text{m}$,
$\underline{C = 3.6\,\text{pF/m}}$

Wire Geometry

- wire spacing
    - or wire diameter
    - strong dependence of $\vec{E}$ field
        - non-uniformity causes
            - $\vec{E}$ variations
            - significant variations of charge to wires
            - wires will shift in position
    - can give 30% variations in gain



Forces can "pull" cathodes toward anodes

- can also cause gain variations

(115) <u>Electrostatic Forces on Wires</u>

Need to ensure wire will tolerate

- V_0 must not produce force that
  - exceeds restoring force from wire tension
    $T \propto d^2$

$$\therefore \boxed{V_0 \leq s\sqrt{\frac{4\pi\epsilon_0 T}{LC}}}$$

- limits 's' → cannot be too small

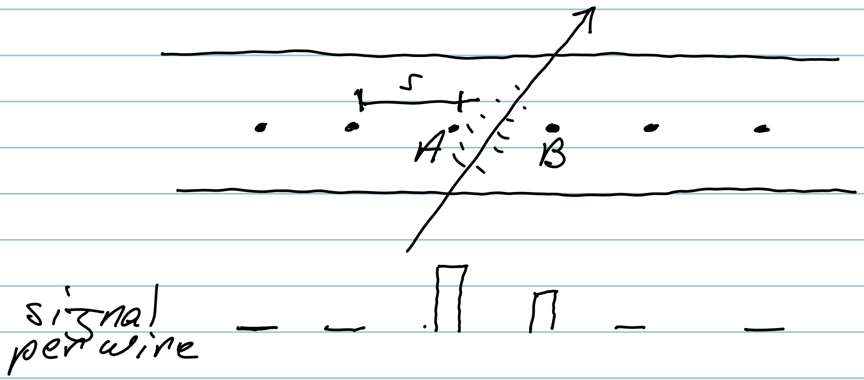
To hold wires stably

$$\boxed{T \geq \left(\frac{V_0 L C}{s}\right)^2 \frac{1}{4\pi\epsilon_0}}$$

These effects on geometry + field must be modeled → + therefore measured

Segmentation + Spatial Resolution

Normally, position resolution limited in direction ⊥ anodes

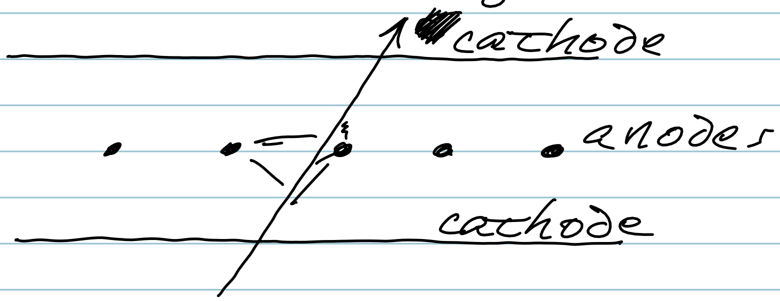


- spatial resolution $\frac{1}{2}s$
  - improvement if interpolate
    i.e. closer to wire 'A' than 'B'
  - – $\boxed{\sigma(x) \sim \frac{s}{\sqrt{12}}}$
    $= 580\,\mu m$ if $s = 2mm$

Drift Chamber

Particle passes thru detector

T_d = travel time of e^-s



- improve spatial resolution
- impact parameter of trajectory to anode
  - drift distance

Consider timing resolution of 2ns and drift velocity ~4cm/μs

- resolution in drift distance

$$\boxed{\sigma_x = v\,\delta t} \sim \underline{\underline{\underline{80\mu m}}}$$

- there ~~are~~ is a wide range of drift velocities

In More Detail...

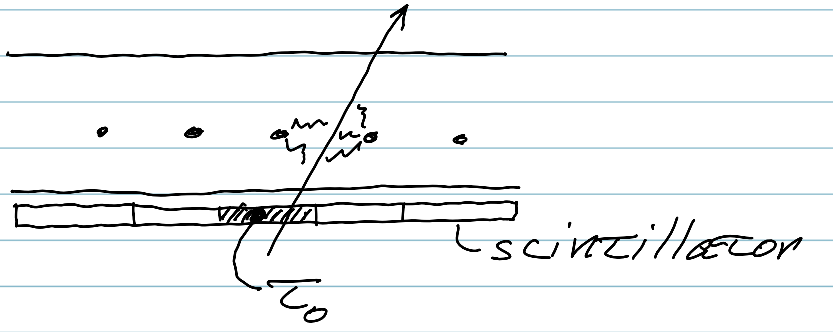
Electric field not strictly constant

- if $W(t)$ is drift velocity as a function of time

$$x = \int_{t_0}^{t_0+t_d} W(t)\,dt$$

- a knowledge of the field
  - allows more precise drift distance

Note: timing reference ~~fram~~ from a fast scintillator signal is possible



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Variation in Drift Velocity

Drift velocity in $\vec{E}$ direction

$$\boxed{W_{\parallel} = \frac{2e|E|}{3m}\left\langle\frac{\lambda}{v}\right\rangle + \frac{1}{3}\frac{e|E|}{m}\frac{d\lambda}{dv}}$$

e, m → charge & mass of e^-

λ = mean free path of e^-
with random velocity, v
- in drift chamber gas

- v randomized by collisions with atoms

- average λ/v over random velocities

In Presence of Magnetic Field

$\vec{B} \perp \vec{E}$ and in direction of anodes

- creates a net drift velocity $\perp$ to $\vec{E}$

$$\boxed{W_\perp = \left(1 + \frac{e^2 B^2 \lambda^2}{m^2 v^2}\right)^{-1} \left(\frac{1}{3} \frac{e|E|}{m} \omega_L \left\langle \frac{\lambda^2}{v^2} \right\rangle\right)}$$

- ignores λ dependence on v
- ω_L is Larmor frequency

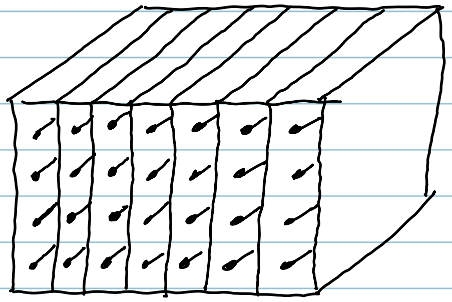
$$\underline{\omega_L = eB/m}$$

Net drift angle relative to $\vec{E}$

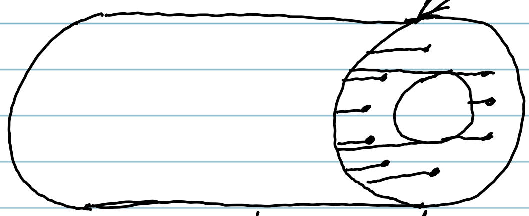
$$\boxed{\tan\alpha = W_\perp / W_\parallel}$$

㉑ Configurations of Detectors

Planar Chambers:



Cylindrical:

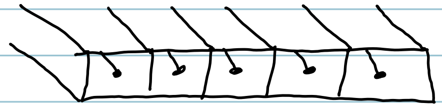


can have many planes of wires

- stereo + axial wires planes

-resolve ghost hits an z-coordinate

Proportional Drift Tubes:



Advantages

-easier construction

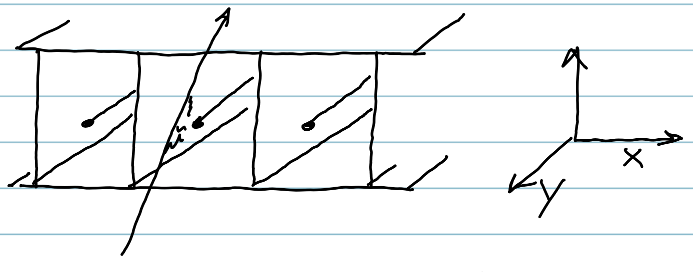
→ cheaper

→ modular

— self supporti~~ng~~ structure

Charge Division to Measure Position

Consider drift tube configuration

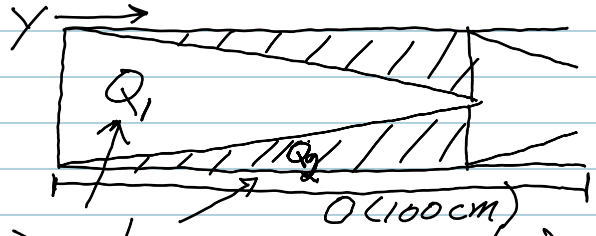


- measure T_d (drift time) → x-coordinate

Second coordinate ⊥ anode plane (y)

- segmented cathodes above and below anodes

'pads' of electrically isolated conductor



- induced charge on cathodes

- measure charges Q_1 and Q_2

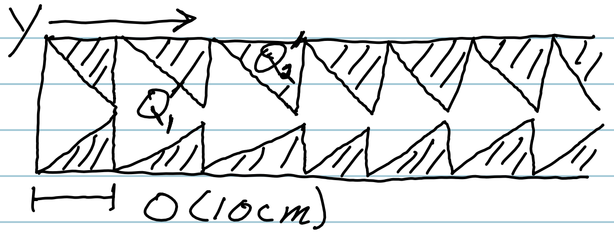
$$\boxed{y \propto \frac{Q_2 - Q_1}{Q_2 + Q_1}}$$

Improving Precision

If pads on top cathode large

- may get precision to within many cm

Segment bottom cathode finer



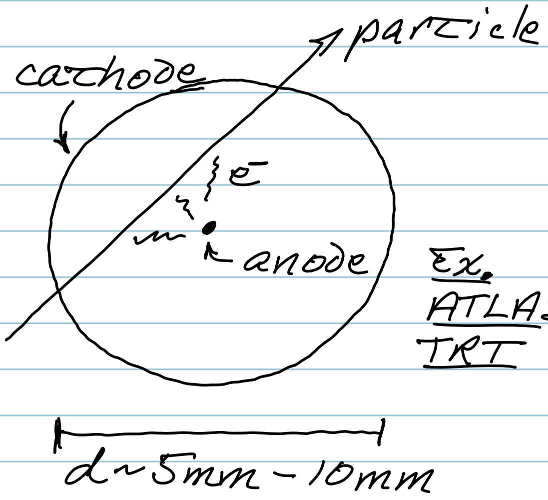
- smallere granularity
  → better localization

- top cathode accurate ~~en~~ enough to indicate bottom pad

- a 20% measurement of charge
  → $\underline{\underline{\delta y \sim \text{few mm}}}$

Straw Tube Detectors

- tube of
  - aluminized mylar (cathode)
- place thin anode down center



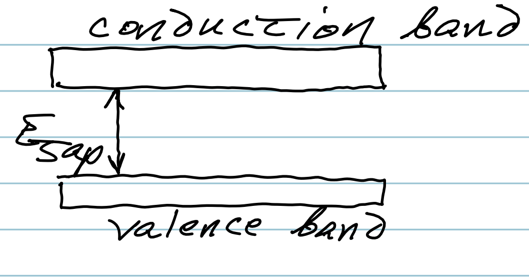
Ex. ATLAS TRT

- can construct very narrow
  - helps in spatial resolution
    - 30μm achieved!

Advantages
- short T_d
  - more responsive for fast data rates
  - B-field has less impact on drift ($\sim W_{\perp}$ small)
- modular construction
- isolation of wires
  - one breaking doesn't affect others

Semiconductor Detectors

Band theory:



- in a semiconductor
  - a modest energy gap, E_{gap} (~1 eV)
  - excitation of e^- in valence band
    - brings them to conduction band (readout)

Modes of excitation

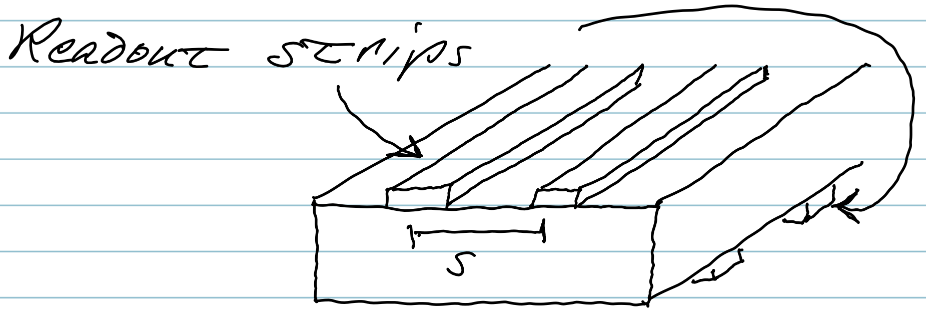
- ionization
  - eg. 90 e-hole pairs per 1 μm of path
  - more ionization than gas detection
    - ∴ better spatial resolution
- photoelectric effect

Electrodes Placement

On surface of semiconductor
- e.g. Si
- to enable readout

Segmentation
- gives positional sensitivity
- strips
- pads } 2D segmentation
- pixels

Silicon Microstrip Detectors



-seperation, s, ~20μ

-gives 10μm spatial resolution

-similar concept to MWPC

Second coordinate

-segment top + bottom planes of strips

-orthogonally

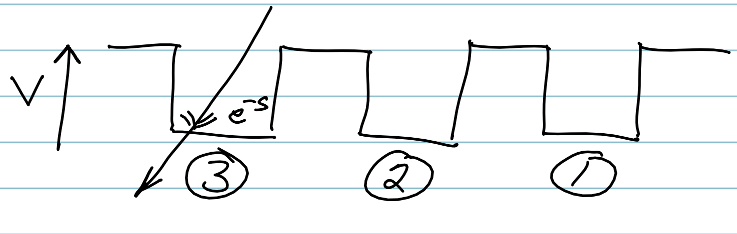
-again, like MWPC

Examples: ATLAS SCT (SemiConductor Tracker)

D0 SMT (Silicon Microstrip Tracker)

Pixel Detectors

Can subdivide chip into seperate
potential wells



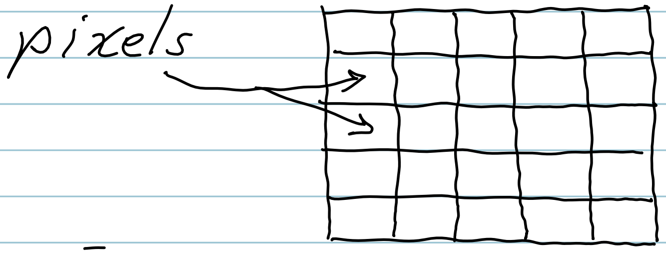
20μm pixel → 5μm spatial
resolution

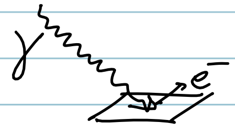
- electrons remain in wells
  - propagate to neighbor only when lower potential

eg, readout ①
→move $e^{-}s$ in ② → ①
→readout ①
→move $e^{-}s$ ③ → ② → ①
...

∴ readout detector pixel
by pixel

Charge-Coupled Devices (CCDs)





Particle physics
- ionization detection
- slow readout
- not many e-hole pairs

Astrophysics
- photoelectric effect
    - sensitive to incident γ's
- resolution: a fraction of a pixel diameter

Example: ROTSE

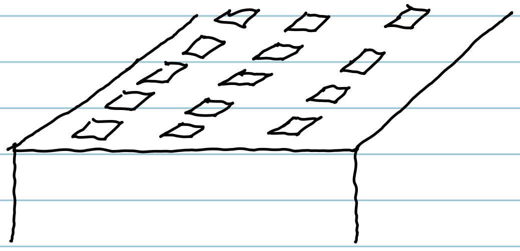
Hybrid Pixel Detector

Try to solve CCD readout time problem

- want to use in high data rate situation
  - want the excellent spatial resolution of pixels

Consider microstrip detector again

- segment each strip in longitudinal direction (ie, along its length)



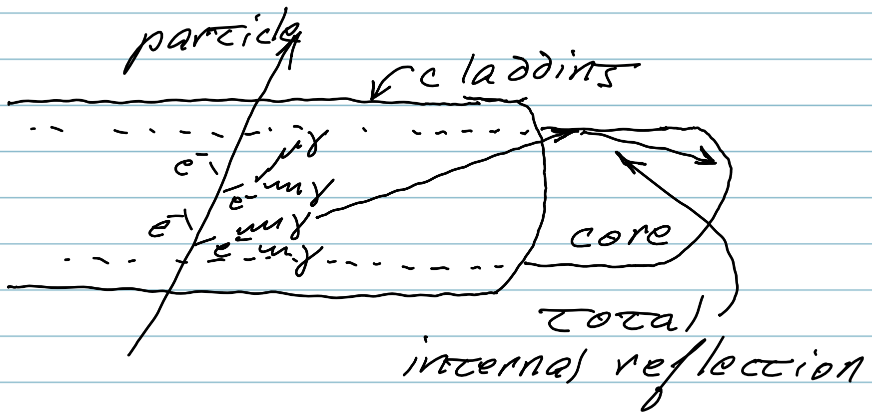
Readout each channel individually → <u>much</u> faster

Example: ATLAS Pixel Detecto

Scintillating Fiber Tracker

A scintillating fiber

- long, optically transparent fiber
- scintillation from additive in fiber
- glass or plastic macaroni's (capillaries)
  - filled with scintillating liquid
  - plastic fiber (e.g. telecommunications)



Condition: $\boxed{n_{air} < n_{clad} < n_{core}}$

Fibers usually 10's μm to ~1 mm

Place fibers ⊥ to path of incident particle

- multiple layers provide measure of particle's trajectory

- can achieve spatial resolutions similar to gaseous detectors
  - → no need for high voltages
  - → modular
  - → fibers readily fabricated

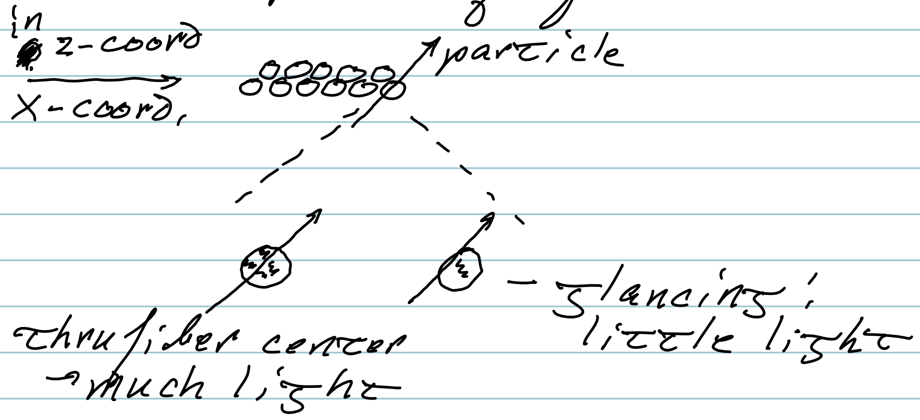
Scintillation light

- very prompt
  - good time resolution
  - appropriate for high rates

- a better fit for tracking than gas drift systems

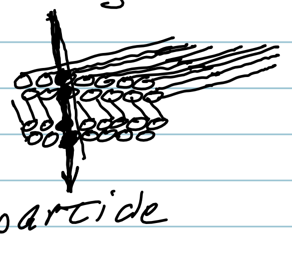
Extracting a Track

Have a plane of fibers



x-coordinate - can use center of fiber, or better to use light yield

Second coordinate (z)
- along fiber
- another layer at stereo angle



pitch angle related to resolution

Example: D0 Central Fiber tracker (CFT)